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Challenges and Configuration of ISRO's Future Q/V Band Satellite

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Abstract— **Broadband technologies are playing a very significant role in the information exchange world. There is a growing trend toward bandwidth-hungry applications driven by data/ video consumption and continuous availability of service. Applications in different areas like in-flight entertainment, maritime connectivity, industrial communications, cellular backhaul via satellite, Internet access to end user, machine-to-machine need unique and innovative solutions to meet their requirements. Demands of this multi-faceted, global broadband infrastructure requirements need to be addressed which can be provided by High throughput broadband satellite communication systems.**

Future broadband satellite systems need to be designed with minimum cost and increased capacity so as to reduce the "service cost per bit" of the end user with respect to the existing systems. The increasing interest from various user groups (the public, businesses, government and defense) for larger bandwidth in satellite communications is prompting the exploitation of higher frequency bands like Ka band as C & Ku band are nearly saturated. Such qualitative evidence is strongly supportive of the use of higher frequencies for satellite communication systems. Capacity enhancement is the key to success, taking into account such factors as throughput, terminals size, rain fade susceptibility etc. Use of Q/V band frequency opens up strong opportunity for offering more cost-effective services, while augmenting the services of Ku, Ka or other bands. In order to realize large-capacity advanced broadband satellite system, use of Q, V and higher bands becomes essential.

This paper critically assesses the need of higher frequency band communication satellites in the interest of Indian Sub-Continent. It highlights the technological challenges involved in Q/V band Spacecraft system design. Also, it highlights the Spacecraft configuration and System features.

Keywords—Satellite communication; Q/V band; Ka band; throughput; Forward link; Return link

I. INTRODUCTION

Indian Space Research Organization (ISRO) is playing a lead role in establishing a strong national communication infrastructure for societal, educational, industrial and entertainment sector applications. Presently, ISRO has standardized various satellite platforms like I-1K, I-2K and I-3K buses to serve different type of requirements. A highly agile and modular next generation Spacecraft bus I-6K with the Lift off Mass (LOM) capability of 4000 kg to 6500 kg is being developed. For Communication Spacecraft, the prime focus is on maximization of the payload content with new and innovative technological advancements for various applications.

The use of various RF frequencies for the satcom applications has steadily increased from the lowest available bands (UHF, L, S, C band) to the higher bands (Ku, Ka). The Higher frequency bands required research and technological advancements to implement. As the available spectrum becomes over-utilized and demand for larger bandwidth is increasing globally, future systems in higher frequency range (30-300 GHz) becomes indispensable. While current systems are predominantly operating in Ka band (20-30 GHz), systems planned for the coming decades initiate operations in the Q band (33-50 GHz), V-Band (50-75 GHz) and W band (75-110 GHz) of the spectrum. These bands are attractive as they offer new avenues (contiguous allocations of 500 MHz to 1 GHz or more) for a wide range of innovative applications.

The exploitation of higher frequency band offers substantial increase in capacity, for all satellite users, public and private. The cost of satellite services should enormously decrease. The most efficient approach to increase the total throughput is by both increasing the RF bandwidth dedicated to user beams and also maximizing the frequency reuse by increasing the number of user beams. The basic principle of satellite communications states that all frequency bands provide the same throughput for the same satellite power same spot beam size, and the same terminal size. Also, at higher frequencies, smaller spot sizes can be achieved easily.

Typical achievable beam width for different frequency bands

- Ku band: between 0.8 deg to 2 deg.
- Ka band: less than 0.5 deg,
- Q band: less than 0.3 deg

In the near future, it is expected that Q/V-band frequency will be used as Gateway link and would allow the use of full Ka band available spectrum for the user link, thereby increasing both the user and gateway available spectrum, with an increase in overall system throughput. And also, by the use of Q/V band for the Gateway link, the interference issue between the user links and the gateways (within the service area) can be eliminated.

For global HTS services over the long term, NSR forecasts HTS capacity demand to increase over to 900 Gbps by 2022, while MEO-HTS segment itself (i.e. O3b) will add another 100 Gbps of leased capacity demand as shown in Fig.1. In terms of specific applications, the most of the forecasted

bandwidth growth is expected to be for serving Broadband Access services through HTS.

Q-band frequency advantages over the Ka-band for data transmission include

- Broad bandwidth for high data rate transfer – as the allocated bandwidth is in excess of 4 GHz, which results in 10 times throughput increase
- Beam width for Q-band is narrower for a given antenna, enabling frequency reuse which results in improved spectral efficiency
- High directivity
- Reduced size of satellite
- Higher gain for same antenna aperture
- Low interference probability
- Reduced number of gateways

II. International Scenario

Current commercial satellites only reach Ka-band and presently there are many multi-beam satellites in orbit, for example: Wildblue-2, Anik-F2, Spaceway-3, AMC-15&16 operating in Ka band, IPSTAR operating in Ku band. These satellites are termed as first generation broadband satellites providing a total capacities upto 20 Gbps. Few satellites go one step further in the cost per bit reduction (through smaller beams and wider transponders) for example, KaSat, Viasat-1, Yahsat-1B. These are termed as second generation broadband satellites providing total capacities from 70 Gbps to 140 Gbps by the use of higher Frequency Reuse factor (FR) (by narrower antenna beams) and improved spectral efficiency and coding schemes.

Italian Space Agency (ASI) has conceived missions at very high frequencies since the 70s. ASI funded ITALSAT F1 Satellite was launched in 1991.

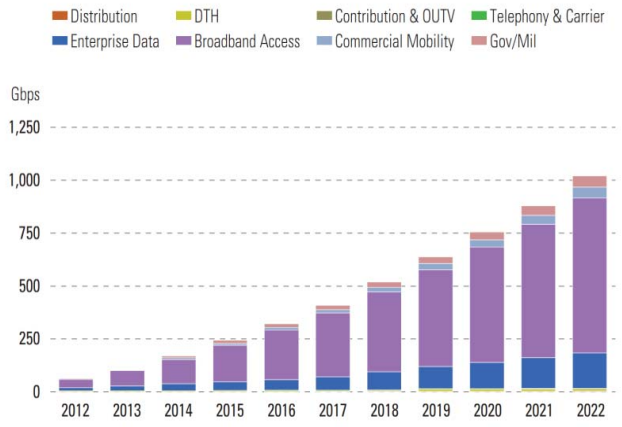

Fig.1 Global HTS & MEO-HTS Bandwidth Demand by Application (Source NSR)

The prime objective of this mission was experimenting advanced digital transmissions at high rate and propagation characterization at higher frequency ranges. Based on ITALSAT, other experimental missions were conceived. In the year 2003, ASI started its Q/V band Payload program which mainly consisted of studies in preparation for a future Q/V band demonstration mission. ASI proposed a Technology Demonstration Payload-5 (TDP-5) on Alphasat mission for the European Space Agency (ESA) in 2005, to perform the following experiments

- Communication experiments (Q/V bands) –for assessing the performance of links at Q/V band
- Propagation experiments (Ka/Q bands) – for obtaining additional Q/V band propagation data
- Technology experiments – to test the technologies required for new payloads in Q/V band.

Advanced Extremely High Frequency (AEHF) is another series of communications satellites consisting of six satellites in geostationary orbits and operating at 44 GHz Uplink (EHF band) and 20 GHz Downlink (SHF band).

III. Indian Perspective

Asia is the world's most populous and fastest growing region, where the demand for communication and entertainment is rising rapidly; satellites need to be well positioned in higher bands to satisfy such demand. India with a population of ~1.3 billion has around 65% people below age group of 35 years who are more tech savvy for broadband applications which necessities the need for higher bandwidth. In Indian context, 'rural broadband will play a crucial role in 'inclusive development'. Efficient satellite based system can address the requirements of Remote/un-served/underserved areas. GEO-HTS projects in Ka Band which are planned to be launched in future will bring about 300 Gbps of HTS supply to Asia by 2020. Fig.2. shows HTS capacity demand for major telecom applications in Asia Pacific. To meet the growing demand for innovative services like Broadband Internet, Interactive multimedia etc., and for overall growth of population both in urban as well as rural areas, ISRO has stepped into Ka band technology.

Over the past two decades ISRO has operationalized satellites providing large capacity of transponders for satcom services in the Indian region. Currently, in India C and Ku-band frequencies are being used for commercial satellite communications and Direct To Home (DTH) services in the country. All these satellite missions are based on ISRO's standard I-1K, I-2K and I-3K bus.

High Throughput Satellite (HTS) systems represent next generation systems capable of delivering very high throughput when compared to Fixed, Broadcast and Mobile Satellite services (FSS, BSS and MSS). This system architecture employs multiple 'spot beams' to cover a desired service area rather than a wide beam. Towards the implementation of

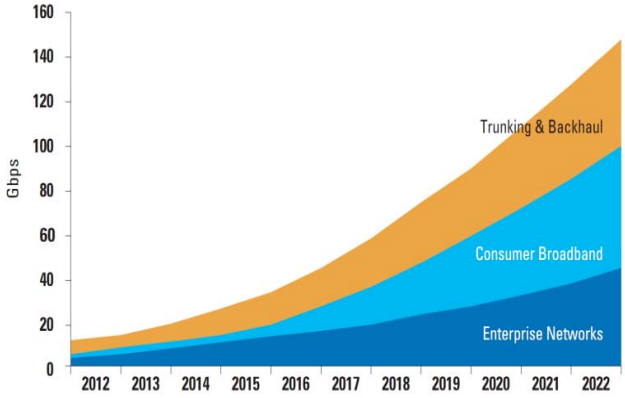

Fig.2 HTS capacity demand for major telecom applications in Asia Pacific (Source Euroconsult)

multi-beam satellite systems, ISRO is developing a state of art next generation highly modular I-6K bus. ISRO is also developing Ku x Ka HTS spacecraft with 36 user beams and 4 Gateway beams providing total throughput of ~15 Gbps. ISRO is actively working on development of Ka x Ka HTS with a total throughput of ~90 Gbps. These spacecrafts will provide broadband system solutions, telecommunication and multimedia service to business and public organizations.

Present satellites of ISRO operate in UHF, L, S, C, Ku and Ka-band. Q/V band will be the next step in satellite communication due to larger bandwidth availability and possible increase of frequency reuse made possible by the higher frequencies.

IV. TECHNOLOGICAL CHALLENGES

Working at millimeter wave frequencies imposes new challenges in the payload hardware designs including the antenna. Some of the technological challenges involved in the design of higher frequency band communication satellites are

A. Antenna design

Antennae are key components in satellite communication systems. Working at millimeter frequencies presents new challenges in the antenna design and its accommodation. At these frequencies generally a horn or reflector antenna is used. The use of higher frequencies requires high output power to compensate for the huge propagation loss and passive circuit losses. The design of high-gain, high-efficiency antennae with very high in-orbit Thermo-mechanical stiffness, low mass, good RF reflectivity and with stringent manufacturing tolerances is very important. This objective is achieved by improvement in structural design, material and manufacturing performance improvements.

Increased beam count/smaller beam diameter (typically 0.3 degree) also places demanding requirements on antenna feeds and reflector designs. Multiple Feed per Beam (MFB) design, Smart antenna concept is the new technologies in the antenna design. MFB technology is becoming more attractive now-a-days for single antenna solution to generate set of adjacent beams. In the conventional Single Feed per Beam (SFB) approach, each beam is created by a single feed horn. In a MFB technique, each spot beam is realized by using a cluster of small feed horns. This simplifies the accommodation of antennae on the Spacecraft. A passive Beam Forming Network (BFN) technique is utilized to power split the RF signals of a beam into coherent signals on the cluster of feeds.

B. Antenna Integration and Alignment

The Integration and alignment of the antenna is quite challenging at higher operating frequency and high directivity of the antenna. The alignment of the feed with respect to the reflector and the reflector with respect to the spacecraft is of high importance. This stringent requirement arises from the need to minimize loss in gain over the contour. The Coverage gain loss vs. Antenna depointing at 48 GHz is shown in Fig. 3.

C. Fabrication and assembly of waveguides

As frequency increases, waveguide dimension reduces. The reduced dimension of the waveguides requires special care during design, fabrication, handling and cleanliness in order to avoid any mechanical stress. Stress on the waveguide would affect the feed positions in turn increasing the pointing error. Hence, during integration sufficient care and an accurate routing to be followed to avoid stress on the waveguides and any misalignment issues.

D. Availability of hardware

Increased count of amplifiers with larger bandwidth is driving the development of more powerful and high efficiency Travelling Wave Tube Amplifiers (TWTAs). The components like Low Noise Amplifier (LNA), High Power Amplifier (HPA) or oscillators which work in higher frequencies has much larger non-linear effects when compared to Ka bands, the losses are also higher. Some innovative solutions for augmentation to Conventional technology need to be adopted to reduce mass, size and power needs. Monolithic Microwave Integrated Circuit (MMIC) technology is considered vital for the design of systems at higher frequency.

Of late MMICs are very popular for amplification and linearization within the Channel Amplifier (CAMP) and HPA.

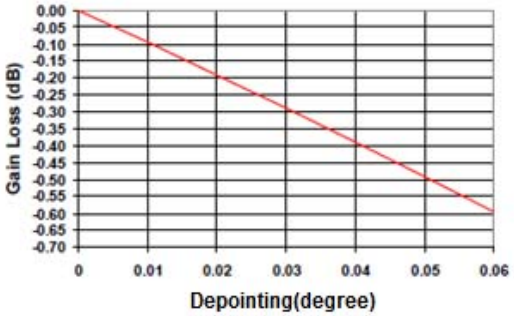

Fig.3 Coverage gain loss Vs. Antenna depointing at 48 GHz

The advantages of MMICs include size reduction when compared to hybrid circuits, leading to reduction in mass of the equipment, low cost and good uniformity. Lack of Maturity of Q/V band technology, and availability of HPA's for commercial missions is a deterrent towards exploiting the higher band frequencies and hence more research activities needed to develop efficient and cost effective systems.

E. On-station payload flexibility

At higher frequencies (Q/V/W-band), there could be large variation in the propagation losses (typically from 5 to 40 dB). The smaller beam size at higher frequency, results in traffic aggregation at beam level and hot spots. Flexible power or spectrum per beam allocation and flexible antenna solutions are very much needed to cope with the traffic demand uncertainties or changes.

Onboard flexibility in power and Spectrum can be achieved through the use of flexible TWTAs or Multi Port Amplifier (MPAs), use of steerable/active antennas and non regular patterns. Use of new generation flexible TWTs provides power efficient Flexible output power keeping the EIRP density constant when increasing/decreasing the bandwidth. This enables to save power for the beam with decreased bandwidth and give it to the beam with increased bandwidth. Coverage flexibility can be achieved through the use of antenna array or phased array antenna which increases the overall gain and provides electronically steerable beams. This calls for a complex BFN technology.

F. Satellite platform accuracy and antenna pointing

Challenges of maintaining the beam to beam isolation becomes stringent for narrower spot beams. Also it calls for stringent pointing accuracy requirements from the antenna orientation point of view. The prime sources for de-pointing which affects the antenna performance are

- Platform stability - This can be addressed by the use of high accuracy star trackers, zero momentum system having 4 wheels in skewed configuration, thereby achieving higher precision platform stability.
- Antenna thermal distortions effects – this results in beam pointing variations which can be counteracted by the use of Closed loop RF tracking system and highly accurate Antenna pointing mechanisms.
- Antenna Alignment - To address integration errors and misalignment issues, individual parts need to be assembled with stringent accuracy. Better alignment techniques such as laser tracker to be adopted to take care of misalignment issues during integration leading to degradation of antenna performance.

G. Satellite platform and Launch vehicle compatibility

The use of high frequencies and narrower spot beams imposes challenges on the platform systems in terms of increased requirement of Payload DC power/dissipation/mass and accommodation capabilities. This calls for very high performance platform systems in terms of handling high power dissipation or innovative solutions need to be worked out to reduce mass and power needs. The capabilities required for the Platform system to support high capacity payload is in the area of thermal subsystem, Propulsion Subsystem, Attitude and Orbit Control Subsystem (AOCS) and Power Subsystem. Innovatitive Thermal solution such as Deployable Thermal Radiators (DTR) and Loop Heat Pipe (LHP) technology for the high dissipating element need to be adopted. Propulsion system calls for introduction of high power Electric Propulsion System (EPS) for orbit raising and station acquisition maneuvers along with its usage in North South Station Keeping (NSSK) operations. Advances in Power subsystem include advanced high efficiency Multi-junction solar cells supported by high capacity Li-ion battery, high voltage (70V) fully regulated bus and power distribution using Bus bars. Advances in AOCS include improvement in the platform stability by the use of high accuracy star trackers, zero momentum system and use of autonomy features.

EPS offers a cost effective solution for larger multi spot beam Spacecrafts and provides longer mission life while reducing the launch mass and the launch cost. Use of EPS for NSSK operation substantially reduces excursions and transients during Station Keeping thereby increasing terminal availability and Quality of Service (QOS).

H. Atmospheric Attenuation

The free space path loss is proportional to the square of the frequency. , but the higher the frequency, higher is the antenna directivity (considering the same antenna dimension), therefore the increase of loss with frequency is compensated by the higher antenna gain. The atmospheric absorption is mainly due to water vapor and oxygen. Rain is the major contributor to the total additive attenuation and hence suitable mitigation techniques shall be adopted.

The fading mitigation techniques are as given below

- Site Diversity
- Uplink Power Control –Uplink fading can be compensated by automatic variation of the ground station Transmit power.
- Adaptive Coding and Modulation (ACM) – automatically varying modulation order and FEC rate to maximize throughput in all link conditions.

V. PROPOSED CONFIGURATION

ISRO has standardised its Satellite platform viz. I-1K, I-2K, I-3K bus. The spacecraft proposed can be built around ISRO's new I-6K bus. This bus is a versatile bus having a modular approach, seperate modules are planned for Bus Systems, Payload Systems and Propulsion Systems providing high level of flexibility and ease in AIT operations. The bus can support LOM from 4000kg to 6500 kg to support mission life of a typical 15 years. The Bus also has a capability to generate and

handle upto 20 kW of power. The bus has several advanced features which can be selected based on mission requirments. The new I-6K bus is compatible with GSLV MK-III and commercial launch vehicles. The Propulsion system which is used for orbit raising and station keeping consists of Bi-propellant system with Mixed Oxides of Nitrogen & Mono-Methyl Hydrazine. To support the mission life of 15 years, EPS with 75mN Hall Effect Thrusters having Isp of 2100secs is proposed for NSSK operations. These electric thrusters shall be equipped with 2 axis Gimbal Mechanism. The power system is conceived as direct energy transfer system with state-of-art Advanced Multi Junction solar cells for sunlit and Battery Discharge Regulator (BDR)/Li-ion battery for eclipse operations. A 70 V fully regulated power system configuration is proposed. Attitude and orbital control system uses state of the art star tracker based zero momentum system in order to achieve higher precision platform stability. A highly efficient closed loop RF tracking system with Antenna Deployment and pointing mechanism is proposed to correct the platform instability errors along with the errors caused due to thermal distortions of reflector, hinge mechanism and residual errors in each reflector.

A typical System architecture and the coverage polygon of the proposed configuration is shown in Fig. 4 and Fig. 5. The proposed payload is based on bentpipe architecture with user beams in Ka band and Gateway beams in Q/V band, The Service area as shown in Fig. 5 is Indian Mainland plus islands including Andaman & Nicobar Islands and Lakshadweep Islands.

The payload configuration is based on four colour frequency reuse scheme. The spectrum for user beam is 1 GHz (in each polarisation), the Gateway spectrum is 2 GHz (in each polarisation). Total of 88 spot beams, each of size ~0.36° is considered for the user link. Total 11 active Gateway beams (11 active + 2 Site Diversity Gateways) are required, each Gateway supporting 8 user beams. Each user beam is of 500 MHz bandwidth (in transmit and Receive) and each beam utilizes single polarisation and hence total allocated user bandwidth (in both polarisation) is 44 GHz. Each TWTA is shared by 2 beams in the forward link and 4 beams share one TWTA in the Return link. The increase in each user beam bandwidth, increases per beam throughput. The higher no. of beams covering the service area, will increase the overall system throughput.

Throughput of the satellite can be computed using the following equation:

$$Capacity\ per\ beam = \frac{Beam\ BW * Spectral\ effeciency * Code\ rate}{Filter\ roll\ off\ factor}$$

Forward Link : Assuming 475 MHz BW per user beam, using 32 APSK modulation at 5/6 code rate with 15% roll off factor, data rate of about 1720 Mbps per beam can be acheieved. Using modems with data rate of 200 Mbps, 8 carriers per beam can be accommodated. In the proposed configuration Effective Forward Link throughput achieved is ~140.8 Gbps.

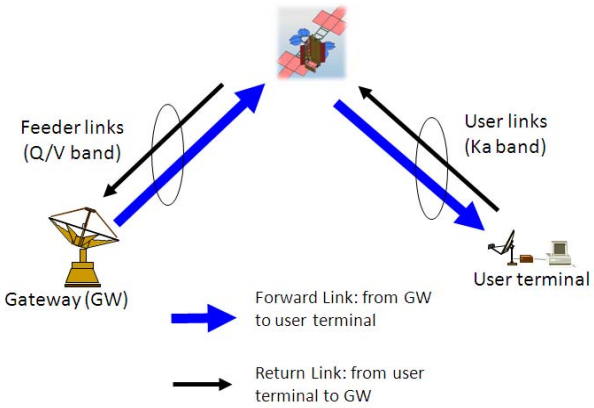

Fig. 4. System level architecture of the proposed configuration

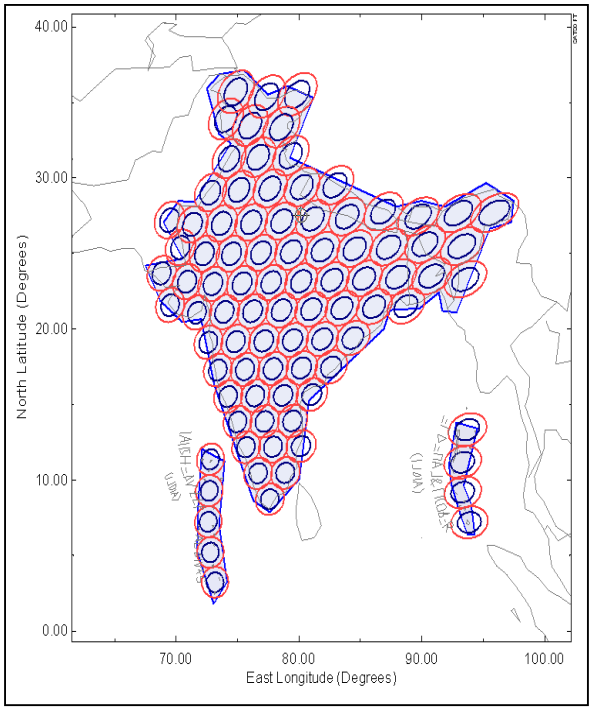

Fig.5. Coverage polygon

Return link : Assuming 475 MHz BW per user beam, each return link TWTA of 2000MHz BW shares four users in a single polarization. Using 16APSK modulation at 5/6 code rate with 15% roll off factor, data rate of about 5507 Mbps per retrun beam TWTA can be achieved. Using modem with data rate of 200Mbps, 27 carriers can be accommodated. In the proposed configuration Effective Return Link throughput achieved is ~118.8 Gbps.

The net throughtput achievable is around ~260 Gbps in clear sky conditions. Use of lower order modulation and adaptive codes rates results in corresponding loss in beam spectral efficiency and net throughput. Considering maximum user Downlink speed of 4Mbps and Uplink speed of 2Mbps, 35200 users can be accomodated simultaneously. With user activity

factor of 1:30, about 1 million users can be catered through the proposed satellite configuration.

VI. CONCLUSION

The increase of satellite throughput is the key to competitiveness. Seeing the market trend and futuristic forecasts, it is imperative to go for higher frequency band Q/V and W band in future. Use of higher frequencies presents technological challenges for the future antenna design, BFN technology, wideband payload equipments (filters, frequency converter and amplifiers), antenna pointing accuracy, apart from managing the systems budgets. With the proposed satellite configuration, the net throughtput achievable is over 260 Gbps.

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